INTEGRATED OPTICAL DEVICE

* * * * *

The present invention generally relates to the field of integrated optics, and particularly to integrated optical devices for Wavelength Division Multiplexing (WDM) optical communication systems. More specifically, the present invention relates to an integrated multiplexer/demultiplexer optical device, for dropping and/or adding optical signals from/to a wavelength division multiplexed optical signal (Optical Add-Drop Multiplexer - shortly OADM).

In WDM optical communications, a plurality of mutually independent optical signals are multiplexed in the optical wavelength domain and sent along a line, comprising optical fibers or integrated waveguides; the signals can be either digital or analogue, and they are distinguished from each other in that each of them has a specific wavelength, distinct from those of the other signals.

In the practice, specific wavelength bands of predetermined amplitude, also referred to as channels, are assigned to each of the signals at different wavelengths. The channels, each identified by a respective wavelength value called the channel central wavelength, have a certain spectral amplitude around the central wavelength value, which depends, in particular, on the characteristics of the signal source laser and on the modulation imparted thereto

for associating an information content with the signal. Typical values of spectral separation between adjacent channels are 1.6 nm and 0.8 nm for the so-called Dense WDM (shortly, DWDM), and 20 nm for Coarse WDM (CWDM - ITU Recommendation No. G.694.2).

Currently, signal processing (multiplexing, demultiplexing, routing) is mainly performed on electrical signals, by means of electronic devices. Optical-electrical-optical conversion of the signals is therefore required. This constitutes the main bottleneck against the increase in the communication band.

Efforts are therefore being made for developing optical devices that are capable of processing the signals directly in the optical domain.

In particular, optical devices (optical demultiplexers), are required that are capable of separating the different channels of a wavelength division multiplexed optical signal travelling on a line, and routing the individual channels to the desired recipients. Similarly, optical devices (optical multiplexers) are necessary for receiving separate channels from distinct sources and combining them into a wavelength division multiplexed signal.

A known technique for realizing this kind of optical devices exploits Bragg filters, *i.e.*, optical filters

obtained by means of Bragg gratings, essentially consisting of alternated regions of different refractive index; when an optical signal is propagated through the filter, some wavelengths are reflected, some others pass through the filter, depending on the grating structure.

Integrated add/drop multiplexing devices are known comprising Bragg gratings realized in the arms of Mach-Zehnder interferometers. One such device is for example described in T. Erdogan et al., "Integrated-optical Mach-Zehnder add-drop filter fabricated by a single UV-induced grating exposure", Applied Optics, Vol. 36, No. 30, 20 Oct. 1997, pages 7838-7845.

The Applicant observes that this device is a low refractive index contrast device.

The Applicant observes that these devices make use of low refractive index contrast Bragg gratings, *i.e.* gratings in which the difference in refractive index of the alternated regions is quite small. For the purposes of the present invention, with grating with a "low refractive index contrast" it is intended a grating wherein the percentage difference $\Delta n = 100 \times (n_2/n_1 - 1)$ [%] between the refractive indexes n_1 and n_2 of the regions of different refractive index (n_1 being the lower value) is lower than 1.5%. Accordingly, in the following of the present description, with "high refractive index contrast" it will be intended a

percentage difference greater of 1.5%.

The Applicant has observed that gratings having low refractive index contrast are adapted to reflect signals in a relatively small wavelength band, and are not particularly indicated for CWDM communications, where the width of each channel is relatively large. In addition to this, low refractive index contrast Bragg gratings have a significant length (the number of alternated regions must be high), which is in contrast with current trend towards high integration.

The Applicant has found that high refractive index contrast Bragg gratings should be preferred. Compared to low refractive index contrast Bragg filters, high refractive index contrast Bragg filters allow obtaining a wider band of reflected wavelengths and a higher reflectivity with a significantly lower number of pairs of alternated regions of different refractive indexes. High refractive index contrast Bragg filters can thus be made more compact than their low refractive index contrast counterparts.

US 4,790,614 discloses a one-chip monolithic multiplex wavelength transmission device. The device exploits a monolithic optical filter obtained by forming in an optical waveguide a plurality of gaps, arranged in the light propagation direction, having period and width equal to multiples of a quarter of wavelength of the propagating

signal, and a depth larger than the thickness of the waveguide. The gaps are filled with a material having a refractive index different from that of the waveguide. The optical filter is designed so as to reflect or transmit the light thereon or therethrough depending on the wavelength characteristics thereof. Light-emitting semiconductor devices or photodetectors are formed monolithically on the light-transmitting and reflecting sides of the waveguide.

The Applicant has observed that using the technique disclosed in that document, high refractive index contrast Bragg gratings can be formed. Two types of Bragg gratings are disclosed in that document: a first type of grating is adapted to create an optical filter having a relatively wide reflection band; a second grating type is intended to create an optical filter having a relatively wide reflection band and, within the reflection band, a transmission band.

In particular, the Applicant has noted that this second type of gratings, intended to create optical filters capable of transmitting a selected range of wavelengths (pass band) within a relatively wide stop band, actually cannot be practically exploited in the field of optical communications, due to the very poor pass band characteristics.

In addition to this, the Applicant has observed that the different embodiments of multiplex device disclosed in

that document are affected by problems due to the fact that, in order to be able to separate and properly route different channels of a wavelength division multiplexed optical signal, the direction of propagation of the signal must be tilted with respect to a direction perpendicular to the grating axis (defined by a direction perpendicular to the interfaces between regions of different refractive indexes, *i.e.* the walls of the gaps forming the optical filter). In other words, the angle of incidence of the optical signal onto the grating that forms the optical filter must be different from zero.

In particular, the Applicant has found that this causes a worsening of the optical filter performance, reducing the effective bandwidth and reducing the slope of the transition between the reflective and the transmissive bands. Additionally, the transversal width of the reflected optical beam is widened, causing a loss of power in the reflected signal.

The Applicant has found that an integrated Mach-Zehnder comprising, on each of the coupled waveguides and in both coupling regions of the device, a grating that is formed by realizing gaps on the entire cross-section of the core of the waveguide and that has a percentace variation of the refractive index of at least 1.5%, is adapted to realize optical multiplexers/demultiplexers, particularly for the

use in WDM communications, and is not affected by the problems of the known devices. The grating structure may advantageoulsy be realized with a still higher refractive index contrast, preferably higher than 10%, more preferably higher than 50%, which provides a spectral response more suitable for the here-considered WDM applications.

The proposed device is rather compact, allows separating different channels of a wavelength division multiplexed signal, and has an angle of incidence of the optical signals onto the optical filters that is equal to zero.

According to an aspect of the present invention, there is provided an integrated optical device as set forth in claim 1.

The integrated optical device of the present invention comprises a first and a second integrated waveguides, each comprising a core and a cladding, which are arranged so as to be in optical coupling relationship in a first and a second spaced-apart coupling regions, and which have respective optically uncoupled waveguide sections in between the first and second coupling regions.

A first and a second modulated refractive index structures are provided, each one formed along a respective uncoupled waveguide section and comprising at least one pair of regions having a first refractive index n_1 and,

respectively, a second refractive index n_2 greater than the first, said regions being adjacent to each other along the respective uncoupled waveguide section.

Said regions comprise a portion of the respective uncoupled waveguide section and a gap formed in the uncoupled waveguide section, the percentage difference $\Delta n = 100 \times (n_2/n_1 - 1)$ [%] between said first and second refractive indexes being greater than 1.5%.

Preferably, the percentage difference is greater than 10 %, more preferably greater than 50%.

The gap extends at least across the entire cross-section of the core of the respective waveguide section.

An interface between the regions of mutually different refractive index is arranged orthogonally to the light propagation direction in the respective uncoupled waveguide section. The problems inherent to tilted directions of incidence of the light onto the modulated refractive index structures are avoided.

The first and second modulated refractive index structures may comprise each a plurality of pairs of regions of mutually different refractive index, arranged in succession along the respective uncoupled waveguide section.

In an embodiment of the invention, at least one of said plurality of pairs of regions is a transmissive pair, adapted to transmitting optical signals with wavelengths

within a prescribed wavelength pass band; the remaining pairs of regions are instead reflective pairs, adapted to reflect optical signals with wavelengths within a prescribed wavelength stop band containing the pass band.

In particular, said pass band corresponds to at least one prescribed channel of a wavelength division multiplexed signal, and said stop band is at least as wide as an overall wavelength spectrum region occupied by the wavelength division multiplexed signal.

In a preferred embodiment, the at least one transmissive pair comprises two or more transmissive pairs, distributed among the reflective pairs. The Applicant has found that this allows achieving a relatively flat pass band.

All the transmissive pairs may have a same optical length in the light propagation direction, or they may have varying optical lengths in the light propagation direction. The Applicant has found that in order to achieve an even flatter pass band, in the first case a number of reflective pairs between adjacent transmissive pairs preferably varies along the respective waveguide section; in the second case, the number of reflective pairs between adjacent transmissive pairs may be kept constant or be varied along the respective waveguide section.

According to preferred embodiments, the optical

coupling regions have optical coupling factors approximately equal to 50%, and the first and the second modulated refractive index structures are located along the respective uncoupled waveguide section in substantially identical positions with respect to the first coupling region.

In particular, the first waveguide has a first input section, adjacent the first coupling region, and the second waveguide has a first and a second output sections, respectively adjacent the second and the first coupling regions. An input wavelength division multiplexed optical signal, including a first optical signal with wavelength in said pass band and entering the device through said first input section is separated into a first output signal, corresponding to said first optical signal, and a second output signal, corresponding to the input wavelength division multiplexed optical signal deprived of the first optical signal, the first and second output signals respectively exiting the device through the first and second output sections.

The first waveguide may further comprise a second input section, adjacent the second coupling region; a second optical signal with wavelength in said pass band and entering the device through said second input section propagates through the device to the second output section.

According to another aspect of the present invention,

there is provided an integrated optical add/drop device as set forth in claim 14. The integrated optical add/drop device is adapted to receiving an input wavelength division multiplexed optical signal including at least a first and a second optical signals differentiated by their wavelength bands, and selectively extracting the first and a second optical signals from the input wavelength division multiplexed optical signal. The device comprises at least a first and a second integrated optical devices according to the present invention, connected in cascade and having differentiated pass bands, corresponding to respective bands of the first and second optical signals.

In particular, the second output section of the first integrated optical device is coupled to the first input section of the second integrated optical device.

According to still another aspect of the present invention, there is provided a process for manufacturing an integrated optical device as set forth in claim 16.

In brief, the process comprises:

forming on a substrate at least a first and a second integrated waveguides, arranged so as to be in optical coupling relationship in a first and a second spaced-apart coupling regions with respective optically uncoupled waveguide sections in between the first and second coupling regions, and

forming along the optically uncoupled waveguide sections respective first and second modulated refractive index regions, comprising each at least one pair of regions of mutually different refractive index, adjacent to each other along the respective waveguide section.

The at least one pair of regions is formed by cutting away a portion of the respective waveguide section for defining a gap between two adjacent portions of the respective waveguide section; a refractive index of the gap is made different from a refractive index of the waveguide section of at least approximately 1.5 %.

In particular said cutting away is performed simultaneously in the optically uncoupled waveguide sections, for example using a mask defining a pattern of cuts to be formed in the optically uncoupled waveguide sections, and selectively removing the optically uncoupled waveguide sections according to the pattern defined by the mask.

The gaps may be filled with a substance having a refractive index different from that of the waveguide sections, such as air, or they may be vacuum emptied.

The features and advantages of the present invention will be made apparent by the following detailed description of some embodiments thereof, provided merely by way of non-limitative examples, which will be made referring to the

attached drawings, wherein:

FIG. 1 is a symbolic representation of a single-channel optical add/drop device;

FIG. 2 is a schematic view of the optical add/drop device of **FIG. 1** realized according to an embodiment of the present invention;

FIG. 3 is a cross-sectional view along the plane **III-III** in **FIG. 2**;

FIG. 4 is a cross-sectional view along the plane **IV-IV** in **FIG. 2**, showing a portion of one of a pair of Bragg gratings formed in the device of **FIG. 2**;

FIG. 5 schematically shows, in cross-sectional view similar to that of **FIG. 4**, a complete Bragg grating structure according to an embodiment of the present invention;

FIG. 6 shows in diagrammatic form an optical response of the Bragg grating of **FIG.5**;

FIGS. 7 and **8** schematically show, respectively in top plan view and in cross-section along the plane **VIII-VIII**, the device of **FIG. 2** at an intermediate step of a manufacturing process according to an embodiment of the present invention;

FIG. 9 schematically shows the operation of the optical add/drop device of **FIG. 2**;

FIG. 10 is a symbolic representation of a four-channel

optical add-drop device; and

FIG. 11 is a schematic view of the four-channel optical add/drop device realized according to an embodiment of the present invention.

With reference to the drawings, and particularly to **FIG. 1**, a single-channel optical add/drop device **101** is a four-port device with two input ports **IP1** and **IP2** and two output ports **OP1** and **OP2**. A first input port **IP1** receives a wavelength division multiplexed optical signal **S_{IN}{S(λ1), S(λ2),…}** made up of a plurality (two or more) of optical signals **S(λ1)**, **S(λ2)**,…. Each of the signals **S(λ1)**, **S(λ2)**,… is assigned a respective wavelength band (also referred to as a channel) centered on a respective wavelength **λ1**, **λ2**,… (also referred to as the channel central wavelength). For example, considering the case of a four-channel CWDM transmission, the channel central wavelengths are 1470 nm, 1490 nm, 1510 nm and 1530 nm.

One of the signals, namely the signal **S(λ1)** in the shown example (with, *e.g.*, λ1 = 1490 nm), is extracted (dropped) from the multiplexed optical signal **S_{IN}{S(λ1), S(λ2),…}** and made available at a first output port **OP1** of the add/drop device **101**; the dropped signal **S(λ1)** can thus be routed to the prescribed recipient, for example a user home appliance such as a television set, a telephone set, a personal computer and the like, wherein the optical signal

is transformed into a corresponding electrical signal by means of a photodetector (not shown). A second input port **IP2** of the add/drop device **101** is adapted to receive an optical signal **S'(λ1)**, generated for example by a user home appliance laser source and centered on the same wavelength **λ1** as the dropped signal **S(λ1)**; the signal **S'(λ1)** is added to the remaining signals **S(λ2),…**, and a new multiplexed signal S_{OUT}**(S'(λ1), S(λ2),…)**, resulting from the combination of the original signals **S(λ2),…** not dropped, and the added signal **S'(λ1)**, is made available at a second output port **OP2** of the add/drop device **101**.

FIG. 2 schematically shows the single-channel add/drop device **101** realized according to an embodiment of the present invention. The device includes a Mach-Zehnder Interferometer, hereinafter shortly referred to as MZI. The MZI comprises a first optical waveguide **201** and a second optical waveguide **203**, arranged so as to be in optical coupling relationship in spaced-apart first and a second optical coupling regions **205** and **207**, wherein the two optical waveguides **201** and **203** are in close proximity to each other. Each optical coupling region **205** and **207** forms a directional coupler, particularly a 50/50 (also referred to as 3 dB) optical coupler: a predetermined fraction, particularly a half, of the optical power propagating along either one of the two waveguides **201** and **203** is transferred

to the other waveguide. Respective sections **209** and **211** of the two optical waveguides **201** and **203** located between the first and the second optical coupling regions **205** and **207**, and sufficiently spaced apart from each other so as to be optically uncoupled, form the interferometer arms. The MZI can thus be seen as formed by two directional optical couplers, joined to each other by two optical waveguide sections (the interferometer arms).

An end **213** of the first waveguide **201**, adjacent the first coupling region **205**, forms the first input port **IP1** of the add/drop device; an opposite end **215** of the first waveguide, adjacent the second coupling region **207**, forms the second input port **IP2**. A first end **217** of the second waveguide **203**, adjacent the second coupling region **207**, forms the first output port **OP1** of the add/drop device; an opposite end **219** of the second waveguide, adjacent the first coupling region **205**, forms the second output port **OP2**.

In accordance with an embodiment of the present invention, the MZI is a monolithic device, integrated in a chip schematically shown in **FIG. 2** and denoted therein by **221**, and the optical waveguides **201** and **203** are integrated planar waveguides; in particular, the waveguides **201** and **203** may be buried waveguides, ridge waveguides or raised strip waveguides. **FIG. 3** shows a schematic cross-sectional view of the MZI along the plane **III-III**, in the exemplary case of

the waveguides **201** and **203** being buried waveguides, particularly silica buried waveguides. The structure comprises a substrate **301**, for example of a semiconductor material such as silicon. Alternatively, the substrate **301** can be made of a dielectric material, a magnetic material or glass.

A lower cladding layer **303** is formed on the substrate **301**. The lower cladding layer **303** is for example made of silica. The cores of the waveguides **201** and **203** are formed by strips of a layer **305** of doped silica; the strips of doped silica layer **305** are immersed in a first upper cladding layer **307** made for example of silica. The first upper cladding layer **307** is covered by a second upper cladding layer **309**, of the same material as the first upper cladding layer. Optical signals are guided by the waveguide cores because of the difference in the refractive indexes of the doped silica layer **305**, having in particular a higher refractive index, and the lower and the first upper cladding layer **303** and **307**, having a lower refractive index. Given a refractive index contrast between the waveguide cores and the cladding layers, the dimensions of the waveguide cores are chosen in such a way to have single-mode waveguides; the thickness of the cladding layers are chosen to reduce the losses, and in particular the thickness of the lower cladding layer is such as to decouple the propagating mode

from the substrate.

Referring back to **FIG. 2**, along each of the two interferometer arms **205** and **207**, a respective Bragg grating **223** and **225** is formed. The Bragg gratings **223** and **225** are designed to have an optical response such that a signal in the channel band centered on a prescribed wavelength, particularly the wavelength λ1 (for example, 1490 nm) can be separated from the signals in the other channel bands, centered on the wavelengths λ2,… (*e.g.*, 1470 nm, 1510 nm and 1530 nm).

In particular, as visible in **FIG. 4**, the Bragg gratings **223** and **225** are formed by providing a longitudinal succession of trenches or gaps **401** along each section **205** and **207** of the waveguides **201** and **203**, in the direction of propagation of the optical signals. The gaps **401** extend from the top surface of the first upper cladding layer **307** down through the doped silica layer **305** and partially into the lower cladding layer **303**. Each Bragg grating **223**, **225** thus comprises gaps **401** alternated to portions **403** of the waveguide core. The gaps **401** may be filled with a fluid, such as air, gas or a liquid, or with other materials, such as glasses or oxides having a desired refractive index, or they may be emptied to create vacuum thereinside. The second upper cladding layer **309** seals the top free open side of the gaps **401**.

The alternation of gaps **401** and portions **403** of the waveguide core forms a structure having a modulated refractive index, capable of performing a filtering in the wavelength domain.

A gap **401** followed, in the propagation direction of the optical signals, by an adjacent waveguide portion, comprised of a portion **403** of the waveguide core and the associated portions of the lower and upper cladding, form an elemental unit of the modulated refractive index structure, and particularly an elemental unit of the Bragg gratings; such an elemental unit will be hereinafter referred to as a cell; in **FIG. 4** only two cells **C** of the Bragg grating **225** are shown, for simplicity.

A cell has a spectral response determined by the overall dimension of the cell in the light propagation direction (**d1** + **d2** in **FIG. 4**), and by the ratio between the dimensions **d1** and **d2** (taking account of the respective refractive indexes).

Let n_1 and n_2 be the refractive indexes of the two regions of the cell, namely the gap **401** and the adjacent waveguide portion **402**; it is intended that n_1 and n_2 are the effective indexes for the propagating mode.

Assuming that the difference between n_1 and n_2 is small (as in low refractive index contrast structures), it can be shown that a cell is transmissive (*i.e.*, a propagating mode

of wavelength λ passes through the cell) if

$$(n_1 d1 + n_2 d2) = m(\lambda/2) + \lambda/4$$

while the cell is reflective (the propagating mode is reflected) if

$$(n_1 d1 + n_2 d2) = m(\lambda/2)$$

where m is a positive integer, commonly referred to as the order of the cell.

Once the dimension **d1** is chosen, these two equations allow determining the dimension **d2** so that the cell is transmissive or reflective:

$$\text{transmissive cell: } d2 = (2m + 1)(\lambda/4n_2) - d1(n_1/n_2)$$

$$\text{reflective cell: } d2 = m(\lambda/2n_2) - d1(n_1/n_2).$$

The Applicant has however observed that these formulas are the result of an approximation, based on the assumption that the refractive index contrast is low. These formulas cannot be applied in the case the difference between n_1 and n_2 is not small, as in high refractive index contrast structures. The Applicant has therefore derived exact conditions that are valid also in the case the difference between n_1 and n_2 is high. In particular, the conditions under which a cell is transmissive are:

$$d1 = m(\lambda/2n_1) \tag{1}$$

or

$$d2 = (\lambda/2\pi n_1)(m\pi + \alpha) \tag{2}$$

where α is a correction factor given by:

$$\alpha = \arctan\{[(1 - \rho^2)\cos\phi_2]/[(1 + \rho^2)\cos\phi_2]\};$$

ρ is the field reflectivity at the interface between the two regions of different refractive indexes of the cell, and ϕ_2 is the phase contribution due to the propagation within the region of dimension **d2** of the cell.

It can be appreciated that if **d1** is chosen to be equal to an integer multiple of half a wavelength of the propagating mode (equation (1)), the cell result to be transmissive irrespective of the value of **d2**. For values of **d1** different from an integer multiple of half a wavelength of the propagating mode, the cell result to be transmissive only if **d2** is chosen according to the equation (2), while the cell result to be reflective if **d2** is chosen according to the following equation:

$$d2 = (\lambda/2\pi n_1)[(m - \tfrac{1}{2})\pi + \alpha] \qquad (3).$$

Using a high refractive index contrast Bragg grating, and properly dimensioning the cells so as to result reflective at a desired wavelength, it is possible to obtain an optical filter adapted to reflect optical signals with wavelengths within a prescribed, relatively wide band (reflection band or stop band) centered on the desired wavelength. A relatively small number of reflective cells is sufficient for achieving a relatively wide stop band and an approximately 100% reflectivity within such a band. On the contrary, this result cannot be achieved using low

refractive index contrast Bragg gratings, because even for large number of reflective cells the width of the stop band would be very limited, and the reflectivity within such a band would not reach 100%.

Defining the refractive index contrast between the two regions of a cell as $\Delta n = 100 \times (n_2/n_1 - 1)$ [%], for the purposes of the present invention a high refractive index contrast means $\Delta n > 1.5$ %.

In the present case, if the filler of the gaps **401** is chosen in such a way to have a refractive index significantly different from that of the doped silica layer **305**, a high refractive index contrast Bragg filter can be obtained. A typical refractive index value of a waveguide core made of doped silica is approximately 1.45 at a wavelength of approximately 1500 nm, while a gap **401** filled with air has a refractive index approximately equal to 1 at that wavelength; the refractive index contrast is thus equal to approximately 45%, *i.e.*, the Bragg grating thus obtained forms a filter having a high refractive index contrast. Other materials can of course be used to fill the gaps **401**, which still allow obtaining a high refractive index contrast structure.

If, among a plurality of cells reflective at the desired stop band central wavelength, at least one cell is placed that is dimensioned to be transmissive at a desired

pass band central wavelength within the stop band, it is possible to obtain an optical filter adapted to reflect optical signals with wavelengths within the stop band, at the same time capable of transmitting optical signals with wavelengths within a prescribed, relatively narrow pass band centered on the pass band central wavelength.

In particular, the stop band may be chosen to extend through the whole spectral region occupied by a wavelength division multiplexed signal having a prescribed number of channels, and the pass band may be chosen to correspond to one or more of the channels of the wavelength division multiplexed signal, with the pass band central wavelength substantially coincident with the respective channel central wavelength.

Although in principle just one transmissive cell, properly dimensioned and inserted among the plurality of reflective cells, is sufficient to create a pass band within the stop band, the Applicant has observed that the lorentzian shape of the resulting pass band is not suitable for practical applications in the field of optical communications, due to the narrowness of the pass band at high transmittivity values, and its slow extinction. The Applicant has observed that a larger and flatter pass band, with faster extinction rate out of the desired wavelength range can be obtained by providing more than just one

transmissive cell, distributed among the reflective cells.

In addition, the Applicant has found that even better results in terms of pass band flatness are obtained if the number of reflective cells placed among the transmissive cells, and/or the dimensions of the transmissive cells are properly chosen.

For example, referring to **FIG. 5**, there is schematically shown, in cross-sectional view similar to that of **FIG. 4**, a Bragg grating structure according to an embodiment of the present invention (also referred to as an apodized Bragg grating structure). The grating comprises sixteen trenches or gaps **401**, defining fifteen cells **C1** - **C15**. The dimensions of the cells **C1** - **C15** are such that some cells, particularly the cells **C2**, **C3**, **C5**, **C6**, **C7**, **C9**, **C10**, **C11**, **C13** and **C14** (denoted as **R** in the drawing) are reflective at the wavelength λ_{SB} (**FIG. 6**), while some other cells, particularly the cells **C1**, **C4**, **C8**, **C12** and **C15** (denoted as **TX**) are transmissive at the wavelength $\lambda_{PB} = \lambda 1$.

In the shown embodiment, the different spectral behaviour of the reflective and transmissive cells is achieved by acting (varying) the dimension of the portions **403** of waveguide core in the cells, while the dimension of the gaps **401** is kept constant and equal to **d1**. In particular, given the dimension **d1**, the dimensions of the portions **403** of waveguide core in the cells are determined

on the basis of the equations (1), (2) and (3) reported previously. In the shown example, the dimension of the portion **403** of waveguide core in all the reflective cells **C2**, **C3**, **C5**, **C6**, **C7**, **C9**, **C10**, **C11**, **C13** and **C14** is set equal to **d21**, and the dimensions of the portion **403** of waveguide core in the transmissive cells **C1**, **C4**, **C8**, **C12** and **C15** are chosen in such a way that the dimension of the portion **403** of waveguide core in the first and the fifth transmissive cells **C1** and **C15** has a first value **d22**, the dimension of the portion **403** of waveguide core in the second and the fourth transmissive cells **C2** and **C12** has a second value **d23** lower than the first value **d22**, and the dimension of the portion **403** of waveguide core in the third transmissive cell **C8** has a third value **d24** higher than the first value **d22**.

In the exemplary Bragg grating shown **FIG. 5**, not only are the dimensions of the transmissive cells varied in the light propagation direction, but also the number of reflective cells between adjacent transmissive cells varies. In particular, two reflective cells are placed between the first two transmissive cells, three reflective cells are placed between the second two transmissive cells and between the third two transmissive cells, and two reflective cells are placed between the last two transmissive cells.

More generally, it can be observed that a transmissive cell constitutes a sort of defect in a regular structure

comprising only reflective cells; such a defect, together with the adjacent reflective cells, acts like a Fabry-Perot resonant cavity with mirrors represented by the reflective cells adjacent the transmissive cells; the light stays in such a cavity for a time related to the cavity length (*i.e.*, the dimension of the transmissive cell) and the mirror reflectivity related to the number of adjacent reflective cells. In order to have a flat pass band, the dimensions of the transmissive cells and the distribution of reflective cells among the transmissive cells shall be such that the distribution of the times of permanence of the light in the cavities is substantially gaussian, with a maximum located substantially at the center of the whole structure. This can be achieved by varying the number of reflective cells (keeping the dimensions and the number of the trasnsmissive cells fixed), so that the reflective cells increase in number in the first half of the grating (adjacent to the first optical coupler **205**), while they decrease in number in the second half of the grating (adjacent the second optical coupler **207**); in particular, the distribution of reflective cells in the second half of the grating can be generically symmetric to the distribution of reflective cells in the first half of the grating. Alternatively, the number of reflective cells between adjacent transmissive cells can be kept constant, and the dimensions of the transmissive cells

be increased towards the center of the grating. In still another alternative, both the transmissive cell dimensions and the number of reflective cells between adjacent transmissive cells can be varied as described above.

In the example of **FIG. 5**, the number of reflective cells increases towards the centre of the grating, while the dimension of the transmissive cells first decreases and then increases.

Based on the previous considerations, Bragg gratings **223, 225** can be formed constituting band-pass filters having a stop band (**SB** in **FIG. 6**) spanning the wavelength range of the wavelength division multiplexed signal, and a pass band (**PB1** or **PB2** in **FIG. 6**) corresponding to one of the channels of the wavelength division multiplexed signal. Optical signals with wavelengths falling within the pass band can pass through the grating substantially unattenuated, while optical signals with wavelengths falling within the stop band are reflected. For example, **FIG. 6** schematically shows the optical response of Bragg gratings adapted to be used in the context of CWDM optical communications, designed to have a stop band **SB** of approximately 90 nm centered on a central stop band wavelength λ_{SB} of approximately 1490 nm, and a pass band **PB1** or **PB2** (of approximately 20 nm) centered on a desired pass band central wavelength **λ1** or **λ2** (1490 or 1470 nm).

The Applicant designed an integrated optical device of the type shown in **FIG. 2**. The thickness of the silica layer forming the lower cladding layer 303 was in the range 10 - 20 μm; the thickness and width of the doped silica layer forming the waveguide cores 305 was approximately 4 - 5 μm; the thickness of the silica layer forming the first upper cladding layer 307 was approximately 10 μm; and the thickness of the silica layer forming the second upper cladding layer 309 was approximately 10 μm. The waveguide cores had a refractive index of 1.454, and the cladding layers had a refractive index of 1.444. The gaps **401** were filled with air. Bragg gratings having each an overall length of 68.39 μm were formed in the interferometer arms, with gaps **401** of 500 nm; the length of the waveguide core **305** sections in the reflective cells was 1.714 μm, the length of the waveguide core sections in the transmissive cells **C1** and **C15** was 8.648 μm, the length of the waveguide core sections in the transmissive cells **C4** and **C12** was 7.621 μm, and the length of the waveguide core sections in the transmissive cell **C8** was 10.702 μm. Experiments conducted on such a grating structure evidenced that the grating provided a quite flat pass band centered on a wavelength of 1490 nm, with rather steep edges. These Bragg gratings are suitable for separating the channel λ1, centered on 1490 nm, from the remaining channels of a Coarse wavelength division

multiplexed signal.

A process for the manufacturing of an add/drop device according to an embodiment of the present invention will be now described. In particular, the process that will be described by way of example refers to the manufacturing of a device in silica buried waveguide technology.

Firstly, the silica layer **303** that will form the lower cladding layer is formed on the silicon substrate **301**; in particular, the layer **303** can be formed by deposition, by means of conventional deposition techniques such as the Chemical Vapour Deposition (CVD), the Flame Hydrolysis Deposition (FHD) or the electron-beam deposition.

Then, the doped silica layer **305** is formed on the lower cladding layer **303**, for example by means of any one of the cited deposition techniques. The doping of the layer is achieved by introducing into the reaction chamber the desired dopants; for example, a germanium-doped silica layer can be obtained by mixing $SiCl_4$ and $GeCl_4$.

The doped silica layer **305** must then be patterned to define the two waveguide cores **201** and **203**. This can be achieved by means of photolithographical techniques: a layer of a photosensible resin (photoresist) is deposited on the layer **305**, and the photoresist layer is then selectively exposed to radiation (typically, UV light) through a suitable mask. The areas of the photoresist that have been

exposed to the radiation are then removed. By means of an etching process, uncovered areas of the doped silica layer **305** are then removed, to define the waveguide cores; the etching process is preferably anisotropic (*e.g.*, Reactive Ion Etching - RIE). After the etching, the photoresist is completely removed.

The first upper cladding layer **307** is then formed on the structure, for example by means of any of the cited deposition techniques.

In this way, a structure including the two buried waveguides **201** and **203** is obtained.

The two Bragg gratings are then formed along the two sections **209**, **211** of the waveguides forming the interferometer arms. Similarly to the definition of the waveguide cores, this is achieved by means of photolithographic techniques. A mask layer is first deposited on top of the first upper cladding layer **307**. **FIGS. 7** and **8** schematically show, respectively in top-plan view and in cross-section along one of the interferometer arms, a portion of the device with the mask layer applied. Reference numeral **701** denotes the mask layer. It can be seen that generically rectangular windows **703** are formed in the mask layer **701**, said windows extending transversally to the interferometer arms. A following etching process allows removing the first upper cladding layer **307**, the doped

silica layer **305** forming the two waveguide cores and part of the lower cladding layer **303** in correspondence of the rectangular gaps in the mask layer **701**. In this way, the gaps **401** schematically shown in **FIG. 4** are formed. In particular, the gaps **401** preferably have a depth that depends on the mode-field diameter (MFD) of the optical signals; preferably, the depth of the gaps is at least equal to twice the MFD: the Applicant has found that in this way the transmittivity is not significantly affected. The etching process is anisotropic, due to the relatively small aspect ratio of the gaps **401** to be formed.

After this step, the mask layer **701** is removed, and the second upper cladding layer **309** is formed on top of the structure, so as to seal the gaps **401**.

It is observed that by means of the process described, the two Bragg gratings are formed simultaneously and can easily be made identical to each other, as well as located substantially at a same longitudinal position along the two interferometer arms.

The Applicant has realized an add/drop device of the type shown in **FIG. 2** in silica buried waveguide technology. The two waveguides **201** and **203** were spaced apart of approximately 5 µm in the regions of the optical couplers **205** and **207**, which had both a length of approximately 1221 µm. The distance between the waveguides in the region of the

interferometer arms was approximately 25 µm. The rectilinear sections of the waveguides were joined together by sinusoidally bent waveguide sections.

The operation of the add/drop device shown in **FIG. 2** will be now explained making reference to the schematic view of **FIG. 9**. Concerning the drop operation, when the multiplexed signal $S_{IN}\{S(\lambda1), S(\lambda2),\ldots\}$, entering the device from the first input port **IP1** and propagating through the first waveguide **201**, reaches the first coupler **205**, a half of the optical power is transferred to the second waveguide **203**; as a consequence, two half-power multiplexed signals, indicated in the drawing as $½[S_{IN}\{S(\lambda1), S(\lambda2),\ldots\}]$, propagate through the first and the second waveguides **201** and **203**, the half-power multiplexed signal propagating through the second waveguide **203** being in phase quadrature ($\pi/2$ phase shift) compared to the half-power multiplexed signal propagating through the first waveguide **201**. When the two half-power signals $½[S_{IN}\{S(\lambda1), S(\lambda2),\ldots\}]$ reach the Bragg gratings **223**, **225** formed in the respective interferometer arm, only the half-power signals $½[S(\lambda1)]$ in the wavelength band centered on the wavelength $\lambda1$ are transmitted, the remaining half-power multiplexed signals (indicated in the drawing by $½[S_{IN}\{S(\lambda2),\ldots\}]$) being reflected. When the two half-power signals $½[S(\lambda1)]$ reach the second optical coupler **207**, an additional $\pi/2$ phase shift causes the full optical power

signal **S(λ1)** to be made available at the first output port **OP1** of the device. For a similar reason, the reflected half-power signals ½[S_{IN}{S(λ2),…}] constructively recombine when they pass back through the first optical coupler **205**, and a full power multiplexed signal S_{IN}{S(λ2),…} is available at the second output port **OP2** of the device.

The device also allows adding a new signal **S'(λ1)**, centered on the same wavelength **λ1** as the dropped signal **S(λ1)**, to the full power multiplexed signal S_{IN}{S(λ2),…}, thereby obtaining the multiplexed output signal S_{OUT}{S'(λ1), S(λ2),…}. If the new signal **S'(λ1)** is fed to the second input port **IP2** of the device and propagated through the first waveguide **201**, when such a signal reaches the second optical coupler **207** a half of the optical power is transferred to the second waveguide **203**; as a consequence, two half-power signals ½[S'(λ1)], in phase quadrature, propagate through the first and the second waveguides **201** and **203**. These half-power signals ½[S'(λ1)] are transmitted by the Bragg grating **223** and **225** formed in the respective interferometer arm. When the signals reaches the first optical coupler **205**, they recombine constructively in the second waveguide **203** and a full-power signal **S'(λ1)** is made available at the second output port **OP2** of the device. This signal, together with the multiplexed signal S_{IN}{S(λ2),…}, forms the multiplexed output signal S_{OUT}{S'(λ1), S(λ2),…}.

It can be appreciated that in the described device, because of the substantial orthogonality between gaps **401** and waveguides **201** and **203**, the angle of incidence of the optical signals onto the gratings is substantially equal to zero.

It is observed that in order to achieve the desired performance, neither the length of the two interferometer arms **209** and **211**, nor the longitudinal position of the Bragg gratings **223** and **225** along the interferometer arms are critical to the device design. However, it is important that the MZI be balanced, *i.e.*, that the two interferometer arms have the same length, and that the two Bragg gratings be identical and identically located longitudinally along the two interferometer arms. The manufacturing process described in the foregoing assures that these conditions are satisfied.

The use of monolithic Bragg grating structures formed by means of relatively deep trenches allows obtaining a high refractive index contrast; these gratings allow achieving satisfactory performances in terms of stop band and pass band with gratings of very small length. Also, manufacturing processes can be devised such that the gratings are identical to each other and identically located along the interferometer arms of the MZI.

By combining a plurality of single-channel add/drop

devices of the type shown in **FIG. 2**, a multi-channel add/drop device can be obtained. For example, **FIG. 10** is a symbolic representation of a four-channel add/drop device; the device comprises an input port **IP1** adapted to receiving a four-channel wavelength division multiplexed signal $S_{IN}\{S(\lambda1), S(\lambda2), S(\lambda3), S(\lambda4)\}$, four output ports (drop ports) **OP11** to **OP14**, each one delivering a respective one of the four signals $S(\lambda1)$, $S(\lambda2)$, $S(\lambda3)$, $S(\lambda4)$ composing the four-channel signal $S_{IN}\{S(\lambda1), S(\lambda2), S(\lambda3), S(\lambda4)\}$, four input ports (add ports) **IP21** to **IP24**, each one adapted to receiving a respective new signal $S'(\lambda1)$, $S'(\lambda2)$, $S'(\lambda3)$, $S'(\lambda4)$ centered on a prescribed one of the four wavelengths $\lambda1$, $\lambda2$, $\lambda3$, $\lambda4$; and an output port **OP2** delivering a new four-channel wavelength division multiplexed signal $S_{OUT}\{S'(\lambda1), S'(\lambda2), S'(\lambda3), S'(\lambda4)\}$ resulting from the combination of the four signals $S'(\lambda1)$, $S'(\lambda2)$, $S'(\lambda3)$, $S'(\lambda4)$.

FIG. 11 schematically shows a four-channel add/drop device realized according to an embodiment of the present invention. The device comprises four single-channel add/drop devices **1011**, **1012**, **1013**, **1014** of the type shown in **FIG. 2**, connected in cascade to each other. A first add/drop device **1011** receives the original four-channel multiplexed signal $S_{IN}\{S(\lambda1), S(\lambda2), S(\lambda3), S(\lambda4)\}$, drops therefrom the signal $S(\lambda1)$, and adds thereto the signal $S'(\lambda1)$, delivering a

four-channel multiplexed signal **S{S'(λ1), S(λ2), S(λ3), S(λ4)}** to a second add/drop device **1012**; the second add/drop device **1012** drops from the multiplexed signal **S{S'(λ1), S(λ2), S(λ3), S(λ4)}** the signal **S(λ2)** and adds thereto the signal **S'(λ2)**, delivering a four-channel multiplexed signal **S{S'(λ1), S'(λ2), S(λ3), S(λ4)}** to a third add/drop device **1013**; the third add/drop device **1013** drops from the multiplexed signal **S{S'(λ1), S'(λ2), S(λ3), S(λ4)}** the signal **S(λ3)** and adds the signal **S'(λ3)**, delivering a new four-channel multiplexed signal **S{S'(λ1), S'(λ2), S'(λ3), S(λ4)}** to a fourth add/drop device **1014**; finally, the fourth add/drop device **1014** drops the signal **S(λ4)** from the multiplexed signal **S{S'(λ1), S'(λ2), S'(λ3), S(λ4)}** and adds thereto the signal **S'(λ4)**, thereby delivering at the output port **OP2** of the device the output four-channel multiplexed signal **S_{OUT}{S'(λ1), S'(λ2), S'(λ3), S'(λ4)}**.

More complex structures can easily be obtained by cascading more single-channel add/drop devices. For example, Bragg gratings having different optical response may be used, *e.g.* gratings that are reflective for two or more channels and transmissive for two or more adjacent channels in the wavelength division multiplexed signal.

Although the present invention has been disclosed and described by way of some embodiments, it is apparent to those skilled in the art that several modifications to the

described embodiments, as well as other embodiments of the present invention are possible without departing from the scope thereof as defined in the appended claims.